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Sand mining impacts on long-term dune erosion in southern Monterey Bay

Edward B. Thornton ^{a,*}, Abby Sallenger ^b, Juan Conforto Sesto ^c, Laura Egley ^d,
Timothy McGee ^e, Rost Parsons ^e

^a Department of Oceanography, Naval Postgraduate School, Monterey, CA 37 93943, United States

^b Center for Coastal and Watershed Studies, United States Geologic Survey, Saint, Petersburg, FL 33701, United States

^c Instituto Hidrografico de la Marina, Plaza de San Severiano, 3, Cadiz 11007, Spain

^d NPMOD Lemoore, K Street Bldg 001 NAS, Lemoore, CA 93246, United States

^e Naval Meteorology and Oceanography Command, Stennis Space Center, MS 39529, United States

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Abstract

Southern Monterey Bay was the most intensively mined shoreline (with sand removed directly from the surf zone) in the U.S. during the period from 1906 until 1990, when the mines were closed following hypotheses that the mining caused coastal erosion. It is estimated that the yearly averaged amount of mined sand between 1940 and 1984 was 128,000 m³/yr, which is approximately 50% of the yearly average dune volume loss during this period. To assess the impact of sand mining, erosion rates along an 18 km range of shoreline during the times of intensive sand mining (1940–1990) are compared with the rates after sand mining ceased (1990–2004). Most of the shoreline is composed of unconsolidated sand with extensive sand dunes rising up to a height of 46 m, vulnerable to the erosive forces of storm waves. Erosion is defined here as a recession of the top edge of the dune. Recession was determined using stereo-photogrammetry, and LIDAR and GPS surveys. Long-term erosion rates vary from about 0.5 m/yr at Monterey to 1.5 m/yr in the middle of the range, and then decrease northward. Erosion events are episodic and occur when storm waves and high tides coincide, allowing swash to undercut the dune and resulting in permanent recession. Erosion appears to be correlated with the occurrence of El Niños. The calculated volume loss of the dune in southern Monterey Bay during the 1997–98 El Niño winter was 1,820,000 m³, which is almost seven times the historical annual mean dune erosion of 270,000 m³/yr. The alongshore variation in recession rates appears to be a function of the alongshore gradient in mean wave energy and depletions by sand mining. After cessation of sand mining in 1990, the erosion rates decreased at locations in the southern end of the bay but have not significantly changed at other locations.

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Keywords: dune erosion; beach erosion; sand mining; Monterey Bay

1. Introduction

The leading anthropogenic cause of sediment loss to the littoral zone in the United States is sand and gravel mining (Magoon et al., 2004). Most of the mining is done in rivers and streams before the sediments reach

* Corresponding author. Tel.: +1 831 656 2847; fax: +1 831 656 2712.

E-mail address: thornton@nps.edu (E.B. Thornton).

the ocean. However, substantial amounts of sand were mined directly from the shoreline until 1990 when it was finally hypothesized that sand mining was a significant contributor to shoreline erosion. The major coastal sand mining in California was along southern Monterey Bay, which started in 1906 at the mouth of the Salinas River and expanded to six commercial sites at Marina and Sand City (Magoon et al., 1972). Only mining from the surf zone is considered here; this does not include mining of the back-beach and dunes that is still ongoing at Marina. Draglines were used to mine the coarse sand deposits within the surf zone, which have a high commercial value. Sand mining was not regulated until 1968, when the State Lands Commission began licensing sand mining operations through the issuance of leases. In addition, the Corps of Engineers began asserting jurisdiction over mining operations in 1974 under the Rivers and Harbors Act of 1899. Both the State Lands and Corps of Engineers mining leases in southern Monterey Bay expired in 1988. An estimated 6.3 million cubic meters of sand was mined before it ceased in 1990 (Magoon et al., 2004). A primary objective of this paper is to assess the impact of sand mining on the erosion of southern Monterey Bay.

Southern Monterey Bay is characterized by a sandy shoreline backed by extensive dunes rising up to 46 m within the Fort Ord and Marina area. The sand dunes, referred to as the Flandarin and pre-Flandarin dunes, were laid down during the Pleistocene from sands originating from the Salinas River, deposited on the exposed continental shelf, and blown onshore by prevailing winds. Approximately 18,000 years ago at a low stand in sea level, these dunes are estimated to have extended 13 km seaward of the present day shoreline (Chin et al., 1988). The shoreline eroded with sea level rise, which equates to an annual recession rate of 0.7 m/yr. Therefore, the southern Monterey Bay shoreline is characterized as an erosive shoreline.

Two littoral cells have been identified in southern Monterey Bay with the demarcation at the Salinas River (Habel and Armstrong, 1978). Refraction of waves over the Monterey submarine canyon and delta offshore of the Salinas river (Fig. 1) results in the mean alongshore sediment transport between the Salinas River and Moss Landing to be directed to the north, most of which eventually empties down the submarine canyon, and the mean alongshore sediment transport south of the Salinas River to be directed to the south. This paper focuses on the southern littoral cell along the 18 km shoreline bounded by Monterey (0 km) and the Salinas River (18 km). The distances alongshore are noted on Fig. 1, and are used as reference locations in the text.

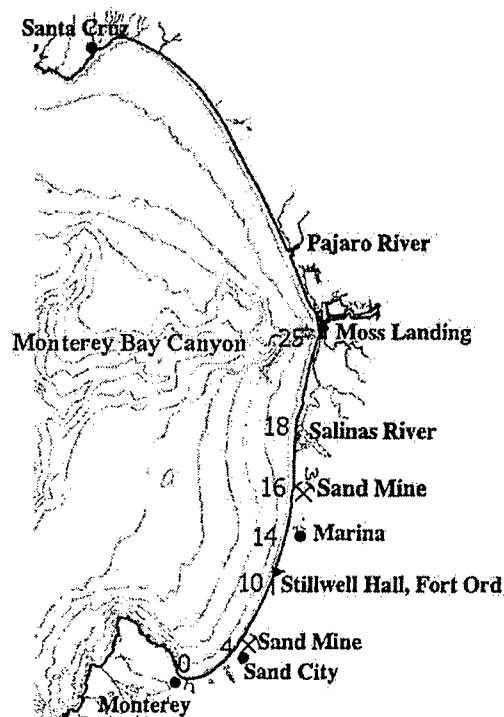


Fig. 1. Monterey Bay shoreline (number of kilometers from Monterey Wharf #2 are indicated) and offshore bathymetry showing the Monterey Bay submarine canyon and the ancient delta off the Salinas River.

Development along this length of shoreline has been limited. A total of approximately 1 km of the shoreline is hardened, which include 50 m of rock revetment to protect culverts and 200 m seawalls to protect a condominium and hotel in Monterey, as well as 100 m of rock rubble and a 200 m concrete wall formed from cement truck tailings in Sand City. In addition, a 200 m rock rubble seawall was constructed to protect Stillwell Hall at Fort Ord in 1978 (Fig. 2), and subsequently removed in March 2004. Armored shorelines neither erode nor contribute sand to the littoral system.

Despite the cessation of sand mining, the beach and dunes are still eroding at a relatively high rate. For example at Fort Ord, a football field existed on the dune between Stillwell Hall (Fig. 2) and the ocean in 1944. After the field eroded into the ocean, rock rubble was placed in front of Stillwell Hall in 1978 and again in 1985 to stop erosion, but even after sand mining ceased, extreme recession continued to occur at the flanks of the rubble. Up to 14 m of recession occurred during the 1997–98 El Niño winter just to the north of Stillwell Hall. Owing to refraction of the prevailing northwest swell over the Monterey submarine canyon, waves converge to form the largest waves in the bay at Fort



Fig. 2. Aerial oblique photo of Stillwell Hall, Fort Ord, California showing rock-rubble sea wall in front and extensive erosion to each side (from USGS 1998).

Ord. These larger waves cause high erosion rates at this location.

The objective of this study is to quantify the impact of sand mining on dune erosion in southern Monterey Bay. To assess this impact, erosion rates during the times of intensive sand mining (1940–1990) are compared with the rates after its cessation (1990–2004). This paper is a compilation of results from various studies (Sklavidis and Lima-Blanco, 1985; McGee, 1986; Oradiwe, 1986; Egley, 2002; Conforto Sesto, 2004) using differing methodologies to survey the dunes of southern Monterey Bay.

2. Methods: measuring dune recession

To obtain an accurate depiction of permanent, long-term erosion, a consistent measurement location must be chosen on the subaerial profile. The waterline is easily identified in aerial photographs, but because of variations in tide elevation and seasonal variability of the shoreline, it is unsuitable as a measurement reference. Similarly, the toe of the dune is often difficult to define owing to material slumping from the dune face. The sharp stereo representation of the dune top edge is not subject to short timescale variability and is used here. The dune top edge for much of the southern Monterey Bay shoreline is easily identified by a vegetation line. Almost the entire 18 km shoreline is adjacent to dunes, which have an average height of ~10 m. The dune slope is at or near the angle of repose because of continual undercutting by waves. Therefore, long-term erosion is defined as the recession of the dune top edge, as this is

the seaward extent of land use. The recession of the dune edge is considered permanent erosion, because the prevailing winds are onshore and there is no modern day mechanism to build out the dune top.

Differing techniques were combined to obtain a dune top recession record spanning the period 1940 to 2004. Mechanical stereo-photogrammetry was used to measure recession from 1940 to 1984. LIDAR survey data of the dunes were obtained spanning the 1997–1998 El Niño winter. The dune top edge was surveyed by walking with a Kinematic GPS in a backpack in 2003. In order to tie together the earlier stereo-photogrammetry studies with recent measurements, stereo-photogrammetry was repeated using digital techniques for the 1984 photos using the same horizontal datum as the LIDAR and GPS surveys. These differing techniques have different accuracies, which are discussed below.

2.1. Stereo-photogrammetry

The erosion in southern Monterey Bay has been measured using photogrammetry by a number of investigators using a variety of methods including mirror-stereoscope (Thompson, 1981), zoom-transfer scope (Jones, 1981), and comparisons with and without field control. Only results obtained using a stereo-comparator with field control are assumed reliable and are presented here.

The erosion rates were quantified using stereo-photogrammetry on 6 sets of aerial photos from 1940 to 1984 to measure dune recession along the southern Monterey Bay shoreline by Sklavidis and Lima-Blanco

(1985) and McGee (1986). These earlier stereo-photogrammetry works used a Zeiss mechanical stereo-comparator interfaced to a PC using digital encoders on the adjustment controls. Photogrammetry errors are due to resolution of the stereo-comparator, image displacement due to relief and tilt, and scale variation. The ground position error (rms radius of the error circle for the two horizontal components) was 0.022 mm, which equates to a 0.2 m error for the 1:12,000 scale photographs used. To minimize tilt displacement errors, only photographs with less than three degrees of tilt were used. To minimize errors of image displacement owing to terrain relief and scale variation, ground control points (GCPs) were selected in the overlapping area of the photo-pair, and scaling points were chosen as close as possible to the measurement region and at nearly the same elevation. The accuracy can be improved by increasing the number of GCPs. GCPs must be identifiable in the images, which makes finding GCPs in the older photos more difficult as these locations may not exist today. In addition, tie-, or homologous, points were used. These are points that can be identified on both photos of the overlapping pair, but whose coordinates are unknown. The GCPs were surveyed using laser ranging for the earlier studies and GPS for the more recent work. The errors for both surveying systems are $O(2 \text{ cm rms})$.

In these earlier studies, the location of the dune top edge was measured continuously (most easily identified by viewing the 3-D image stereoscopically) for sufficient distance alongshore (200–1300 m) to give a representative mean recession rate for sections of shoreline. The elevation of the toe of the dune was measured also so that the height of the dune could be determined. A problem with continuing the recession measurements from the earlier works of Sklavidis and Lima-Blanco (1985) and McGee (1986) was that the absolute horizontal datum was lost, so there is no way to tie together this work with more recent LIDAR and GPS measurements. Therefore, to tie the earlier work with newer measurements, the 1984 photos were redone using modern digital stereo-photogrammetry with the same datum as the LIDAR measurements. Unfortunately, several of the photos were lost, which did not allow completion of the surveys at Fort Ord.

Digital stereo-photogrammetry methods and their associated errors are similar to those of the older mechanical system. The 1984 photos were digitized at $14 \mu\text{m/pixel}$, which gives a 0.3 m resolution. The program automatically finds homologous points at random locations within the pairs of photos and calculates the location and elevation to generate a 3-D

map of the area. The digital terrain model is not as accurate in areas where it is difficult to find homologous points, such as on the beach where the texture is uniform. In addition, because the photo pairs were not taken simultaneously and the waves on the sea surface move between pictures, the algorithm tries to match homologous points that are at different locations, generating erroneous elevations. Erroneous points on the sea surface and the low contrast beach have to be edited. Removing points resulted in some places having too few points to generate an accurate model. Therefore, points had to be manually added using stereographic viewing of the ortho-rectified image pairs to identify and measure elevations at selected points.

The digital stereo-photogrammetry data are acquired at irregular spacing and converted to Universal Transverse Mercator (UTM) coordinates. A rectangular grid is interpolated from the irregularly spaced data using Triangulated Irregular Networks and applying the Delaunay triangulation method. The elevation data points are determined using an inverse distance weighting between adjacent points (Watson and Philip, 1985).

The Imagine OrthoBase software employed in the stereo-photogrammetry calculated total horizontal rms errors ranging from 0.5 to 2 m. The error in determining the dune edge position is calculated using the method of Moore and Griggs (2002). Assuming the rectification and dune edge position have a bivariate normal distribution, the horizontal error is conservatively estimated to be $\pm 2 \text{ m rms}$. The same error is attributed to both the digital and the higher resolution manual stereo-photogrammetry.

2.2. LIDAR measurements

The U.S. Geological Survey (USGS), National Aeronautics and Space Administration and National Oceanic and Atmospheric Administration collaborated to measure coastal change using Airborne Topographic Mapping (ATM) LIDAR to survey the pre- and post-storm topography of the 1997–98 El Niño winter (Oct. 12–13, 1997 and April 15, 17–18, 1998). The ATM system is combined with GPS and inertial navigation to determine position and orientation of the aircraft. The ATM spatial resolution depends on the height and speed of the airplane, laser scan rate, scan angle, and field of view. Errors include system calibration and panoramic distortion. Meridith et al. (1999) discuss the calibration requirements of the ATM, which include corrections for the laser range and angular mounting biases with respect to the aircraft attitude. Elevation errors of less than 15 cm rms were found when LIDAR elevations were

compared with ground surveys, and horizontal accuracy was within 0.8 m with airplane flying at 700 m (Meridith et al., 1999). Stockdon et al. (2002) found a LIDAR horizontal rms error of 1.4 m compared with ground based surveys in determining shoreline position, which is the error estimate used here for dune top edge determination.

Egley (2002) used the LIDAR data to study the erosion along the southern Monterey Bay shoreline before and after the 1997–98 El Niño winter. The LIDAR obtains elevations at arbitrary horizontal locations, so the analysis is treated in the same manner as the digital stereo-photogrammetry. The data were gridded at 1 m resolution, which generally over-sampled the data. There are larger errors in the LIDAR data at the edges of the scan, which generally were over water and in the back dunes. To reduce errors, these areas were masked out. Masking was accomplished by overlaying the LIDAR images onto digital orthophoto quadrangles generated from black and white aerial photographs taken on 21 August 1998. The photographs were scanned to yield a 0.5 m pixel resolution. USGS 7.5 min quadrangle data and USGS digital elevation model data were used as the control. The accuracy and repeatability of this LIDAR data are demonstrated by comparing 1997 and 1998 profiles that bisect the rock revetment and the Stillwell Hall building, which are fixed (Fig. 3). The profiles are able to distinguish the building's irregular roof and chimney, and little variation is found between profiles. Some differences between the 1997 and 1998 profiles are expected because the profiles do not exactly overlay each other; this results in relatively large differences where steep gradients (vertical walls) occur.

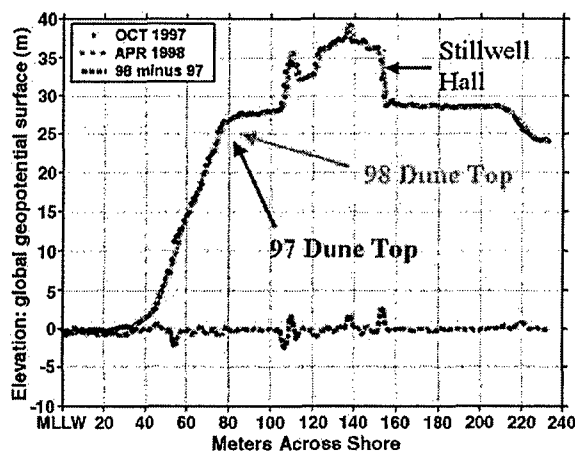


Fig. 3. LIDAR cross-shore profiles in 1997 and 1998 across the hardened shoreline and Stillwell Hall building at Fort Ord, California, demonstrating the repeatability of the measurements.

2.3. GPS surveys

The dune top edge was surveyed by a walker equipped with a Kinematic GPS in a backpack in 2003. The surveyor walked approximately 50 cm from the edge, and the 50 cm was subtracted from the surveys. The toe of the dune was surveyed at the same time with GPS mounted on an ATV. The toe height is determined at the base of dune where the dune face changes from near angle of repose to the milder sloping beach profile. The toe height is most easily identified in early spring after winter waves have cleared off the beach waste. This contrasts with in the fall when the toe is not as easily identified owing to the summer beach berm and rounding of the toe. No recession of the dunes was observed to occur during the 2003–2004 winter, so the December 2003 survey is given a date of 2004 in subsequent analysis.

The accuracy of Kinematic GPS is 5 cm rms in all three directions. Errors occur due to the surveyor not standing straight when climbing the dune top edge and not walking the prescribed distance from the dune edge (the height of the GPS antennae from the ground when the surveyor is standing straight and the 50 cm walking distance from edge are subtracted). It is estimated that the horizontal position error is ± 30 cm. This technique is more accurate than stereo-photogrammetry and LIDAR, and has the added advantage of the surveyor directly observing where the dune top edge and toe are located.

In summary, the horizontal accuracies are estimated ± 2 m for stereo-photogrammetry (mechanical and digital), ± 1.4 m for the LIDAR and ± 0.3 m for walking the dune with Kinematic GPS. Thus, the large dune recessions spanning several years between surveys along Southern Monterey Bay are resolved at $O(1$ m/yr).

3. Dune recession analysis

The objective of the analysis is to determine the long-term recession rate of the dune top edge. Erosion varies spatially alongshore for both the long-term mean and for the short-term seasonal variation. An example of the short-term variability is obtained from the elevation differences calculated between 1997 and 1998 LIDAR measurements for 4 km of shoreline at alongshore distances 6 to 10 km (Fig. 4). The red is an indication of at least 10 m elevation change, which occurs on the dune face, and is therefore an indication of significant dune recession. The alongshore variation occurs on a scale of 200–500 m, associated with large scale shoreline cusps that are erosion features of rip currents of the same



Fig. 4. Elevation differences measured with LIDAR between 1997 and 1998 for 4 km of shoreline centered on Fort Ord. Red and yellow indicate dune erosion, green is no change and blue indicates beach accretion. Large alongshore variations in erosion are indicated.

alongshore spacing (Thornton et al., submitted for publication). The observed short-scale dune erosion occurs at the embayment of these large beach cusps where the beach is the narrowest. The strong variability requires sampling the shoreline at close intervals to avoid aliasing. To obtain a good average for dune recession, the dune top edge was measured continuously alongshore for the stereo-photogrammetry and dune walk for sections of the shoreline ranging from 200 to 1300 m. For the LIDAR data, it was found that cross-shore profiles could be edited more easily to maintain quality control and reduce errors, so the dune recession is determined from the LIDAR-derived profiles every 25 m so as not to alias the data.

In the LIDAR data, the dune top edge is identified as a sharp change in slope in the cross-shore profiles, which is not always obvious. For example, the 1997 and 1998 profiles are compared at a location just north of Stillwell Hall at Fort Ord (Fig. 5), where a large 14 m recession occurred. The dune top edge in 1998 is easy to identify after the recent severe winter erosion. However, the dune top edge in the fall of 1997 is not as obvious, because significant erosion has not occurred recently and the edge has been rounded by wind and rain. This

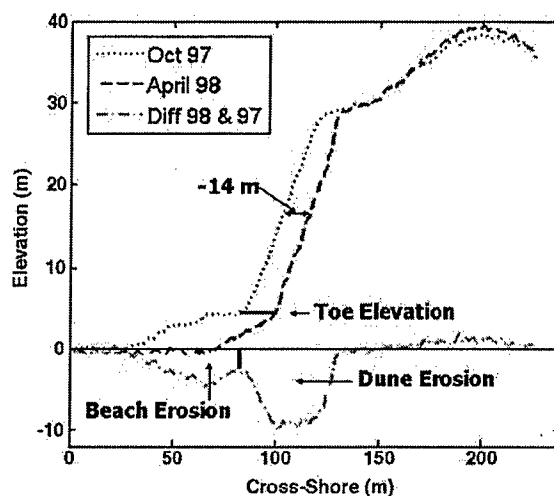


Fig. 5. Cross-shore profiles from LIDAR for 1997 and 1998. The beach and dune erosion are the differences of profile areas and are partitioned at the toe.

leads to some subjectivity in specifying the dune top edge from the profiles. In these cases, a mean recession is more easily measured from the recession of the sloping dune faces (Fig. 5).

The dune top edge is most easily identified on vegetated dune tops, which gives a high contrast in the photographs. The stereo analysis also assisted in the identification of the dune edge where large changes in elevation are easy to identify. The dune top edge is difficult to identify at blow-out locations where there is no vegetation and the dune top is rounded. Identifying the dune top edge at blow-outs was similarly difficult during the walking surveys. Therefore, only sections of

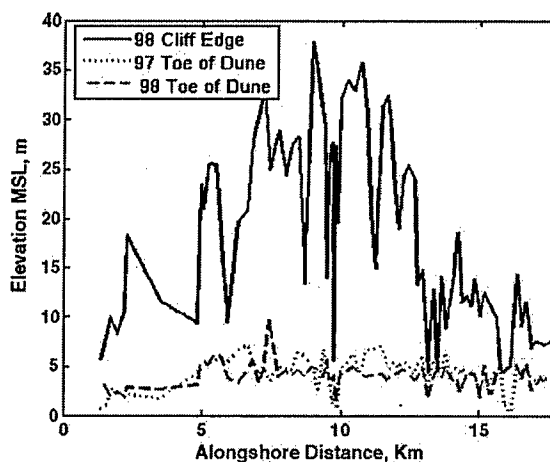


Fig. 6. Elevations of dune top edge in April 1998 and toe in October 1997 and April 1998 relative to MSL as a function of distance alongshore in southern Monterey Bay.

shoreline where the dune top was vegetated are analyzed, which is the majority of the shoreline.

The alongshore variation of the dune top edge and toe elevations measured from the LIDAR profiles for 1997 and 1998 are shown in Fig. 6. Only the elevation of the dune top edge for 1998 is shown, as it varied little from 1997 (even though there was significant recession). However, the dune top edge elevation varies considerably alongshore with elevations up to 9 m in Monterey, 10 m in Sand City, 35 m in Fort Ord, and 15 m in Marina. The toe elevation is low near Monterey and increases to the north, similar to the wave energy. Interestingly, although there were large changes in the beach volume, the mean toe elevation is similar before and after the winter storms with an average of 4.2 m and 4.1 above MSL for 1997 and 1998. The height of the toe suggests that dune erosion only occurs when extreme swash run-up by storm waves coincides with high tides to reach the dune toe (maximum high tide is $\sim +1$ m relative to MSL).

Dune top recessions between the 1940s and 2005, averaged over lengths of shoreline (see Table 1), are plotted against the year the data were acquired at four selected locations in Fig. 7. Average recession rate is measured as the slope of the linear regression line. For most places the dune top edge is steadily recessing. Accretion is observed to have occurred for limited periods at alongshore locations 4 km (within Sand City) and at 13.5 km (in Marina) (Table 1). However, both locations were in an area of sand mining operations where anthropogenic changes occurred. The average recession rates alongshore range from 0.5 to 1.5 m/yr.

The volume of dune erosion is determined using the trapezoidal rule, multiplying the average dune recession by the dune height for sections of the shoreline analyzed from the stereo-photogrammetry and walking surveys. The dune height was measured as the dune top edge elevation minus the toe elevation. The toe elevation was determined from stereo and LIDAR

Table 1
Recession of dune top edge (meters) along Southern Monterey Bay shoreline

	Location (km)								
	1	3	4	5.2	6	8	9.8	10.2	13.5
Length (m)	579	201	540	350	335	692	350	335	1283
Year									
1940			0			0			0
1946	0	0		0	0		0	0	
1956	5.5	8.9	−7.5	25.0	28.0	17.4	19.8	35.7	15.8
1966	12.2	12.8		45.1	48.8	17.5	40.8	45.1	
1970			24.7						31.5
1976	17.2	16.8	32.0	61.0	61.3		48.5	55.8	
1978	19.5	21.2		66.3	66.7		51.4	60.4	
1980						33.4			8.5
1984	23.1	33.4	48.1	74.2	75.5	48.8	62.4	85.3	17.0
Length (m)	1550	1350	550		190	1475			400
1997	23.4		59.7		88.7	53.9			30.2
1998	25.1	36.6	59.1		88.7	57.8			37.5
2004	25.4	38.7	64.8		90.6	63.6			46.4
Average recession rate (m/yr)									
1940–1984	0.61	0.74	1.19	1.94	1.93	0.93	1.57	1.89	0.30
+/-	0.15	0.16	0.12	0.20	0.20	0.13	0.19	0.20	0.11
1984–2004	0.11	0.26	0.83		0.80	0.70			1.43
+/-	0.13	0.15	0.17		0.17	0.15			0.18
<i>t</i> -statistic ^a	−5.11	−1.15	−2.65		−72.49	−27.11			22.67

Location is distance from Wharf #2 in Monterey. Length is alongshore distance over which recession is averaged. Average recession rates based on linear regression along with uncertainty are given for 1940–1984 during the time of intense mining, and for 1984–2004 after the cessation of sand mining.

^a The *t*-statistic is statistically significant at 95% confidence for values $<|4.3|$, based on a two-sided hypothesis test with 2 degrees of freedom.

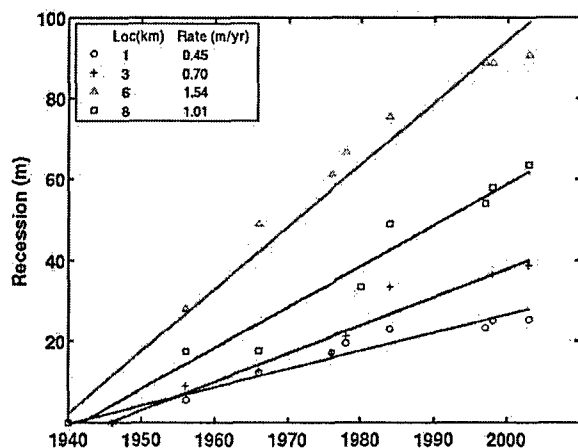


Fig. 7. Mean recession of dune top edge along selected sections of beach (alongshore location in km from Monterey Wharf #2, see also Table 1). The mean recession rate is calculated as the slope of the linear regression line.

terrain models and from surveys of the base of the dune using a Kinematic GPS mounted on an ATV. For the LIDAR data, the change in volume of the dunes and beaches between 1997 and 1998 was measured directly from the profile changes (see Fig. 5) and integrated alongshore.

4. Results: dune erosion rates

The average dune erosion from 1940 to 1984 from Monterey to the Salinas River is calculated as a historical reference value during the time of intensive sand mining, which includes the El Niño events during winters of 1957–58 and 1982–83. The mean annual dune volume loss (volume per unit length of shoreline) is obtained by multiplying the measured mean recession rate, R , by the mean dune height, H (dune top edge minus toe elevations) for each section of beach (Fig. 8). The volume loss is most dependent on the dune height. The total yearly averaged volume of the sand eroded from the dunes in southern Monterey Bay during this 44-year period is obtained by integrating 18 km alongshore and is measured to be 270,000 m³/yr.

The dune loss during the 1997–98 El Niño was an extreme erosion event (Fig. 9), as it was a time of anomalously high tides and high wave energy resulting in significant erosion. Large dune recessions were observed at Fort Ord and Marina, as well as significant recessions at Monterey and Sand City. Starting from the south, recessions at Monterey ranged from 0 to 4 m. Sand City recession ranged from 0 to 2 m. Fort Ord had cuts ranging from 0.5 to 13 m. Large variations in dune recession occurred alongshore. The historical mean annual dune

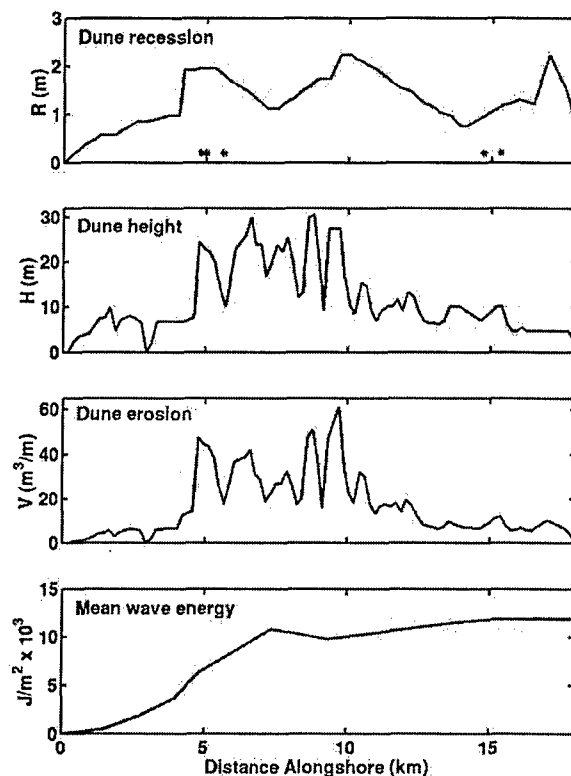


Fig. 8. Annual mean dune top edge recession R with locations of sand mining operations indicated by (*) (top panel), dune height H (top middle panel), volume of dune loss per unit distance V (bottom middle panel), and yearly mean wave energy (bottom panel) versus distance alongshore in southern Monterey Bay.

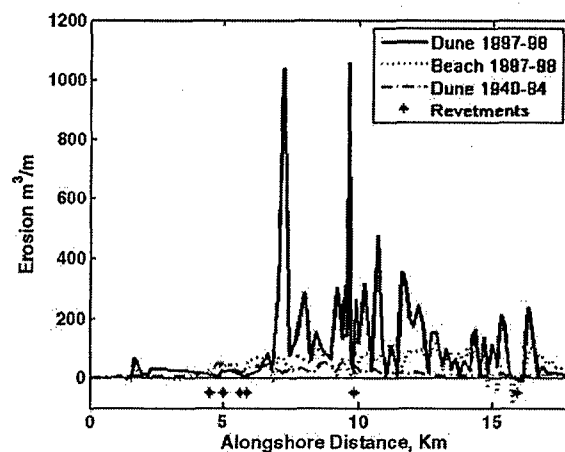


Fig. 9. Alongshore variations in volume loss in southern Monterey Bay of the dune (solid line) and beach (dotted line) measured using LIDAR during the 1997–98 El Niño winter compared with average annual historical dune volume loss (1940–84) measured using stereo-photogrammetry (dashed line). Revetments or seawalls (100–200 m in length) denoted by (*).

volume loss for 1940–1984 is shown for comparison in Fig. 9. Volume loss is also partitioned into permanent erosion of the dune and seasonal beach change for the LIDAR-derived profiles. The seasonal beach change is defined as the profile differences occurring between the shoreline at mean-lower-low water level and the toe of the dune. The total volume loss during the 1997–98 winter was 2,593,000 m³, obtained by integrating the erosion alongshore, of which 1,820,000 m³ is dune loss and 773,000 m³ is beach loss. The dune volume loss during this El Niño winter was almost seven times the historical average annual rate. This emphasizes that erosion can be highly episodic in time, which is not obvious in the regression plots of Fig. 7.

The beach loss of 773,000 m³ is about 40% of the dune loss. The eroded beach sand goes offshore in the winter, building the bar. Sand is moved onshore by the summer swell waves, but there is some permanent loss to the offshore.

5. Discussion: Dune erosion mechanics

Dune erosion is episodic and only occurs when storm waves coincide with high tides to allow the swash to reach and undercut the base of the sand dune. Swash is dependent on wave height (energy) and period and beach slope. The beach slope in turn is dependent on sand grain size and wave energy. It is assumed that long-term wave statistics are steady-state and that sand grain size does not change locally. Mean sea level rise (time scale of centuries) is assumed constant, and that it causes a constant contribution to the rate of dune erosion. It is further assumed that the beaches are in dynamic equilibrium over time owing to a constant supply of sand to the littoral system. This assumption is supported by the observation that the beach widths in southern Monterey Bay appear to be in a long-term (1930–2001) steady-state (Reid, 2004). Therefore, it is hypothesized that any long-term temporal variation in dune recession rates is associated with changes in the amount of sand mined from the surf zone.

Dune erosion varies alongshore. Mechanisms that may explain long-term spatial variability of dune recession include alongshore variations in wave energy, runoff of rainfall, beach slope, width and toe elevation, and variations in the amounts of sand mined. These various mechanisms are discussed next.

5.1. Waves, tides and El Niño events

Wave energy varies spatially over kilometer scales going from small waves at the southernmost part of the

bay in the shadow of a headland to larger waves in the middle of the southern bay, where convergence of waves owing to refraction over Monterey Bay Submarine Canyon results in increased wave heights. Wave refraction across the canyon causes focusing and defocusing of wave energy, depending on wave direction and period. Spatial variability was examined by calculating wave energy at 10 locations in southern Monterey Bay (Oradiwe, 1986). The calculations were based on directional spectra calculated using the Wave Information Studies (WIS) (Resio, 1981) for the twenty year period 1956–1975 and the U.S. Navy Spectral Wave Ocean Model (SWOM) for the eighteen year period 1964–1981. Both models used wind fields generated for the Northern Hemisphere by the U.S. Navy at the Fleet Numerical Meteorology and Oceanography Center to calculate directional wave fields. This precludes swell waves from the Southern Hemisphere, which is a reasonable approach since southern Monterey Bay is protected from waves from the south by the Point Pinos headland (Fig. 1). The directional spectra for every 6 h at a location in deep water outside Monterey Bay were then refracted to shore locations within the bay using linear refraction at one-degree increments over all incident angles of approach. Energy was calculated by integrating the individual directional wave spectra over the sea-swell band (0.05–0.3 Hz and directions), and then averaging over 25 years.¹

Severe refraction occurs as the predominant waves from the northwest pass over the Monterey Submarine Canyon, resulting in focusing of wave energy at Marina and Fort Ord and defocusing of energy at Monterey and Moss Landing. The shorelines of Monterey and Sand City are sheltered by Point Piños for waves from the south and west quadrants and receive a reduced amount of wave energy. The net result is a large alongshore energy gradient, with small waves at Monterey increasing to large waves at Fort Ord and Marina (Fig. 8, lower panel). The dune recession (Fig. 8, top panel) has an alongshore distribution similar to the mean wave energy. This suggests that a primary reason for alongshore variability of erosion is due to the gradient of wave energy.

Wave energy also varies in time. Wave energy and erosion are typically greater during El Niño winters. An El Niño winter occurred at the onset of the study in 1940–41 followed by events in 1957–58, 1982–83, and

¹ Although this is a limited 25-year data set (not previously published, but available) based on using a second generation wave model, the purpose of this analysis is to demonstrate the alongshore gradient of the annual mean energy and not the actual magnitudes.

1997–98. El Niño Southern Oscillation (ENSO) is characterized by weak easterly trade winds, anomalously high sea surface temperatures, high sea level elevations, large rainfall, and large waves along the central California coast (Storlazzi and Griggs, 1998). The incident wave directions were more westerly during 1982–83 and 1997–98 El Niños, which is significant because the shoreline in the middle of the bay is more vulnerable to waves from the west owing to refraction effects.

The potential for erosion increases with increased water level. Mean sea levels tend to be anomalously high during El Niños, a phenomenon that is attributed to a wave of warm water propagating northward along the coast (Flick, 1998). The warm water is piled against the coast to balance the colder, denser water offshore. The sea level records at Monterey only date back to 1973, but San Francisco sea level records started in 1853. Comparing monthly averaged mean sea level from 1973 to 2003 between Monterey and San Francisco, a regression slope of 0.8 is obtained with a correlation coefficient of 0.9. Therefore, the San Francisco record is used to infer sea level at Monterey with a reduced elevation of 0.8. The dune recession at south Fort Ord is compared with temporal changes in MSL (Fig. 10). The inferred monthly averaged MSL record shows large variations coincident with El Niño events. Increased erosion coincides with El Niño events, during which time the MSL is anomalously high with increased storm waves.

Beach profiles at 11 locations within Monterey Bay were measured by Dingler and Reiss (2001) starting in 1983 just after an El Niño winter and ending in 1998 just after another El Niño winter. They found that during El

Niños waves cut back the beach that allowed the swash to attack the dune. The dune retreat at Fort Ord was 21 m between February 1983 and March 1998. Of that retreat, 8 m occurred between February and April 1983 and 9 m over the 1997–98 winter, both during El Niños, and only 4 m during the intervening 14 years. They found that the beach widths required about 2 years to recover from severe erosion after the 1982–83 El Niño. The erosion was greater during the 1982–83 El Niño because storm durations were greater and they occurred during the highest tides.

In summary, storms and higher MSL during El Niño events appear to be a primary cause for coastal erosion. Large erosion occurs during El Niño winters, followed by several ‘normal’ years with less erosion until a new El Niño event occurs again, increasing recession. The long-term erosion rate, composed of episodic El Niño high-erosion-rate years and ‘normal’ erosion years, averages to a recession trend that tends to be constant for a particular location.

5.2. Rainfall and runoff

Casual observation of the shoreline reveals that increased erosion occurs at specific locations where runoff occurs, which is often where the vegetation on the dune has been destroyed by walking paths to the beach (access locations are approximately every 1–2 km alongshore). This leads to the dune being washed onto the beach. High rainfall is associated with the occurrence of El Niños, further exacerbating erosion during these times. However, erosion due to runoff, although not quantified, is considered small compared with erosion due to waves.

5.3. Beach toe elevation

Sallenger et al. (2001) used LIDAR to measure the toe elevation of the dune (T_d) along a 55 km reach of the northern Outer Banks of NC and found that long-term erosion correlated negatively with T_d , i.e., larger erosion occurred for small T_d where run-up can attack the foredune more easily than where T_d is higher. In addition to this cross-shore process, it was found that where there was a deficit of sand, there were lower dunes, which may be related to gradients in alongshore sediment transport. Hence, there may be a feedback between cross-shore erosion processes and alongshore sediment transport gradients. Wave climate along this stretch of open North Carolina coastline is essentially uniform. This contrasts with processes in southern Monterey Bay, where there is plentiful sand (from the

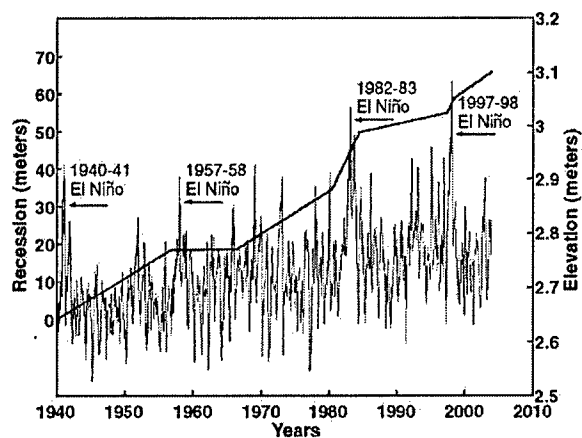


Fig. 10. South Fort Ord dune recession (left ordinate) for 1940–2004 (line) compared with monthly average mean sea level (right ordinate with arbitrary datum) at San Francisco. El Niño winters are indicated.

dune) and a large gradient of wave energy, where both erosion and T_d are positively correlated with wave energy. Hence, larger erosion occurs where wave energy is larger and T_d is higher, just the opposite of what Sallenger et al. (2001) observed.

5.4. Sand mining impact

Although the shoreline in Monterey Bay has historically eroded as sea level has risen, sand mining operations appear to have exacerbated the record of

erosion. Sand was continuously extracted from the shoreface starting in 1906 and continued until the late 1980s, when surf zone sand mining ceased in both Sand City and Marina. The mined sand ranged in size from 10 mm pebbles to 0.15 mm fine sands. The median grain size mined at both Sand City and Marina was approximately 0.85 mm. The sands at both locations are generally finer in the summer months when finer sands are moved shoreward by summer swell waves, during which time the operations were sometimes suspended. In this area, the sand is transported

Table 2
Estimated rates of surf zone sand mining ($\text{m}^3/\text{yr} \times 10^3$)

	Sand City			Approx. total		
	Monterey ^a Sand Co.	Granite ^b Const. Co.	Lone Star ^c Industries			
Loc. (km)	4.8	5.0	5.6			
Year						
27–40	?	?	?			?
40s	15	0	25			40
50s	30–40	15	45–55			100
60s	30–40	15	45–55			100
70s	27	0	60–65 (76) ^f			90
80–83	19 (57) ^e	0	60–70 (76) ^f			84
84	30 ^d (57) ^e	0	31 ^d (76) ^f			61
85	17 ^d	0	32 ^d			49
86	18 ^d	0	34 ^d			52
87	18	0	0			18
88	18	0	0			18
89	18	0	0			18
90	0	0	0			0
	Marina		Approx. total	Approx. total of all operations		
	Monterey ^g Sand Co.	Seaside Sand ^h and Gravel		Min	Est.	Max
Loc. (km)	14.7	15.3				
Year						
44–50	30	0	30	35	70	115
51–57	30	0	30	65	130	220
57–60	30	25	55	78	155	220
60s	30–40	25–30	62	81	162	220
70s	27 (57) ^e	25–30	55	73	145	220
80–83	19 (57) ^e	25–30	46	65	130	220
84	18	0	18	40	79	190
85	18	0	18	35	67	190
86	18	0	18	35	70	190
87	0	0	0	10	18	40
88	0	0	0	10	18	40
89	0	0	0	10	18	40
90	0	0	0	0	0	0

^a Started in 1931, took over by Monterey Sand Co. in 1950 and ceased mining 1990.

^b Started in about 1949–1950 and ceased mining 1968 (pers. com. Cotchett, Granite Construction Co.).

^c Started in 1927, increased production in the late 40's and ceased mining 12/31/86.

^d Actual amounts based on pers. com Robinette, Monterey Sand Co., 1988.

^e U.S. Army Corps of Engineers permit maximum: Dec 1968–July 1988.

^f U.S. Army Corps of Engineers permit maximum: Dec 1968–July 1990.

^g Mined 1944–1986.

^h Mined 1957–1980?

alongshore to the south due to the predominant waves from the northwest. Griggs and Savoy (1985) suggest that sand mining reduced the shore-connected shoals that are prevalent along this shoreline, which protect the beach by dissipating the winter storm wave energy within the surf zone. The lack of shore-connected shoals would allow the wave energy to reach the shore more easily and erode the beach and dune face. In this manner, it is hypothesized that sand mining contributed to dune erosion.

Estimates of the amount of sand mined from the surf zone vary. The U.S. Army Corps of Engineers (1985) estimated that a total of 540,000 m³ were mined prior to 1959 and that about 60,000 m³ were mined in 1959. Dorman (1968) estimated 76,000 m³/yr, whereas Arnal et al. (1973) estimated 190,000–230,000 m³/yr. The amount of sand mined is difficult to accurately determine as the mining companies went to court and made the records proprietary, ostensibly to insure there was no price fixing. Information on the amounts of sand mined was provided for the Sand City operations through personal communication with the mine operators just prior to the closing of the mines (Robinette, 1987; Battalio, 1989), and this information is the basis for the estimates in Table 2. The estimates for the Marina operations are based on the values provided in Sand City, as the operations were similar. The maximum estimate is based on the maximum amount allowed in the U.S. Army Corps of Engineers lease of 76,000 m³/yr by Lone Star Industries in Sand City for the years from 1968 to 1988 and 115,000 m³/yr by the combined Monterey Sand Company operations at Sand City and Marina for the years 1968–1990. Sand mining leases were not renewed after 1988, as it was hypothesized that the mining contributed to erosion (Griggs and Jones, 1985). It is assumed in the lease request that the miners conservatively overestimated their needs. The minimum is assumed to be simply 50% of the best estimate. Based on the best estimate, the total yearly averaged sand mined during the intensive 1940–1984 mining period was 128,000 m³/yr, which is equivalent to almost 50% of the 270,000 m³/yr average dune loss.

The slopes of the recession plots are examined to determine if the rate of recession (slope) has changed since sand mining stopped. The dune top recessions are compared with the amount of sand mined at the combined Sand City operations in Fig. 11 and at the combined Marina operations in Fig. 12 (summarized in Table 1). The errors in the measurements (given earlier) are indicated by the dimensions of the symbols with a time uncertainty of ± 0.5 years. The uncertainty in slope is estimated as the difference in the minimum and

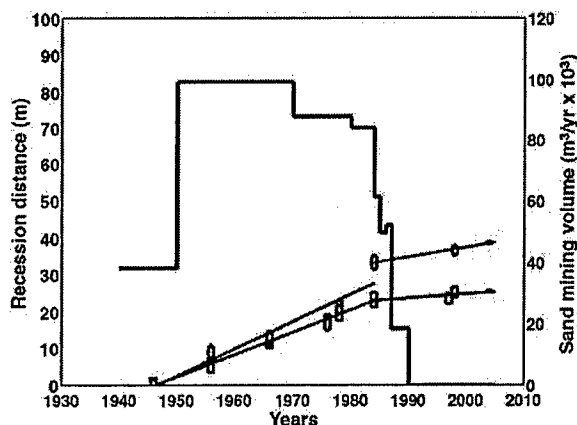


Fig. 11. Recession of dune top dune edge at locations 1 km (rectangles) and 3 km (ellipses), and the total amount of sand mined at Sand City operations at locations 4.8–5.6 km (see Table 2). Regression slopes have been calculated separately between 1940s–1984 during time of intensive sand mining and 1984–2004 after intensive mining (see Table 1). Uncertainties are indicated by dimensions of symbols.

maximum slopes calculated as a regression on the minimum and maximum measurement uncertainties. Examining the evolution of erosion rates, there appears to be at least a qualitative decrease in the regression slopes for 1984–2004 after sand mining stopped compared with the regression slopes of 1940s–1984, during the time of intensive sand mining. Hypothesis tests were applied to determine whether the regression slopes have changed using a two-sided *t*-distribution test (see for example, Bowker and Lieberman, 1961). The slopes and *t*-statistic values are given in Table 1. For locations between Monterey and Sand City at alongshore distances 3 km (Fig. 11) and 4 km, there are statistically significant decreases in the slopes. For locations between Sand City and Marina at alongshore distances 6 and 8 km (Fig. 12), there is a qualitative decrease in slopes, but they are not statistically significant. Therefore, it is concluded that sand mining increased erosion, at least south of Sand City mining operations.

Sand extraction can be viewed as “digging a hole” in the surf zone, and it would be expected that sand would be drawn from both upcoast and downcoast as well as onshore and offshore to fill the hole (Dean, 2004). However, since alongshore transport of sand is generally to the south along this shoreline, it would be expected the hole would be filled more by the upcoast drift. The southerly transport of sand intercepted by the mining would reduce available sand to the beaches to the south of the mining operations. Therefore, it would be expected that locations south of mining operations would be more affected.

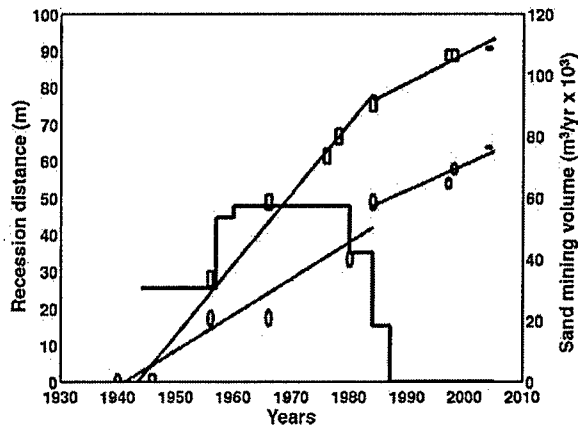


Fig. 12. Recession of dune top edge at locations 6 km (rectangles) and 8 km (ellipses), and total amount of sand mined at Marina operations at locations 14.7–15.3 km (solid line) (see Table 2). Regression slopes have been calculated separately between 1940s–1984 during time of intensive sand mining and 1984–2004 after intensive mining (see Table 1). Uncertainties are indicated by dimensions of symbols.

A possible reason that the rate of erosion has decreased between Monterey and Sand City is because the average 81,000 m³/yr of sand mined at Sand City during the intensive mining years of 1940–1984 was nearly twice the average amount of 47,000 m³/yr mined at Marina during the same time period. While during this same time, the average rate of recession for locations south of the Sand City mines (averaged over locations 1, 3, and 4 km) was 0.85 m/yr compared with the average rate of recession for locations south of the Marina mines (averaged over locations 6 and 8 km) of 1.43 m/yr (see Tables 1 and 2). The expected impact of stopping sand mining would be greater south of Sand City where the erosion rate was lower, but the volume of sand mining was greater, compared with the larger erosion rates and lower amounts of sand mined south of the Marina area. Therefore, it is concluded that sand mining increased the mean recession rates, and also affected the alongshore variation in recession owing to the different amounts of sand extracted at the two sites.

It was pointed out earlier that erosion is not spatially or temporally constant. At most sites, there was an increase in recession between the measurements just prior to 1984 and again between 1997 and 1998, which coincide with the 1982–83 and 1997–98 El Niños. There are only four data points between 1984 and 2004, resulting in only two degrees of freedom on the *t*-statistic. Therefore, a large change in slope is required to have a statistically significant change, even though the erosion rate qualitatively appears to have decreased

everywhere. The highly episodic wave climate complicates relating the volume of sand extracted by mining operations with volumes of sand eroded along the coast.

6. Summary and conclusions

Long-term erosion rates were measured along 18 km of shoreline in Southern Monterey Bay from 1940 to 2004. Erosion is defined here as a recession of the top edge of the dune. Dune erosion occurs when storm waves and high tides coincide to undercut the base of the sand dune causing the dune to slump onto the beach. This results in permanent recession. Dune erosion varied spatially alongshore for both the long-term mean, over kilometer scales, and for the short-term seasonal variation over scales O(200 m). Erosion occurred along the entire 18 km shoreline and varied alongshore at long-term rates that increase from about 0.5 m/yr at Monterey to 1.5 m/yr near Fort Ord and then decrease further north. Causes examined to explain the spatial variation in erosion are: concentration of wave energy, fluctuations in mean sea level, changes in rainfall, and the amount of historical sand mining. It is concluded that the primary reason for alongshore variation in recession rates is the gradient in mean wave energy going from small waves at Monterey, which is sheltered by Point Piños, to larger waves northward.

Erosion is highly episodic. Erosion events are enhanced during stormy winters and particularly during El Niño periods, when prolonged storm waves coinciding with high tides and elevated sea level erode the protective beach and berm, exposing the dune to wave run-up and undercutting. Dune recession appears to be correlated with variations in mean sea level. Mean sea level is increased during El Niño winters. The calculated volume loss of the dune in southern Monterey Bay during the 1997–98 El Niño winter was 1,820,000 m³, which is almost seven times the historical mean annual dune loss of 270,000 m³/yr. Although during an El Niño winter an increase in the erosion rate can be observed, the preceding and following non-El Niño years compensate for this increase with lower erosion rates, keeping the overall historical trend consistent.

The Southern Monterey Bay surf zone was intensively sand mined starting in the early 1900s and continuing until 1990. It was hypothesized that sand mining was a primary cause of erosion in southern Monterey Bay during this time. The best estimate of total average yearly mined sand during the intensive mining years 1940–1984 is 128,000 m³/yr, which is equivalent to approximately 50% of the yearly averaged

dune volume loss during this period. Since sand mining stopped, the erosion rates qualitatively decreased with a significant (at 95% confidence) decrease south of the sand mining operations in Sand City but not significant change at Marina to the north. The alongshore changes in erosion since the cessation of sand mining are partly due to almost twice as much sand being mined at Sand City as compared with Marina. Attempts to determine average recession rates since the cessation of sand mining are complicated by severe erosion occurring during the 1997–98 El Niño winter. Although erosion rates may have slowed as the result of cessation of sand mining, significant recession continues to occur, particularly during times of El Niño winters.

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